Flavor Violation Tests of Warped/Composite SM in the Two-Site Approach Part II

Lijun Zhu

University of Maryland-College Park

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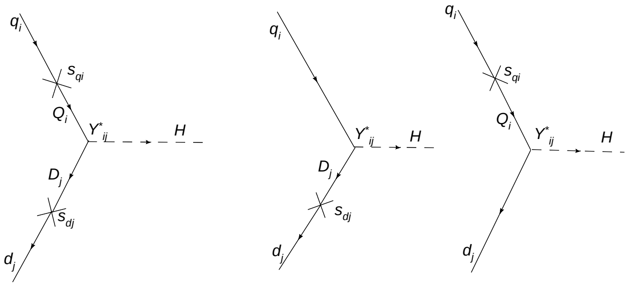
Outline

Flavor structure of Two-site model

- No flavor violation in elementary sector.
- Flavor anarchy in composite sector. (Composite site Yukawa couplings are of the same order and have no structure)
- Hierarchical mixing between elementary and composite sector generate hierarchical quark masses and CKM mixing angles.

Flavor violating Higgs coupling

- Couplings between Higgs and quarks:



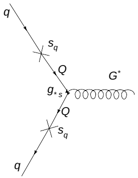
$$Y^*_{ij} H(\bar{q}^i_L d^j_R s_{qi} s_{dj} + \bar{Q}^i_L d^j_R s_{dj} + \bar{q}^i_L \tilde{D}^j_R s_{qi})$$

$$\Rightarrow m^d_{ij} = \frac{v}{\sqrt{2}} Y^*_{ij} s_{qi} s_{dj} \tag{1}$$

$$\Rightarrow D_{L\,ij} \sim s_{qi}/s_{q_j} \qquad ; \qquad D_{R\,ij} \sim s_{di}/s_{dj} \tag{2}$$

Flavor violating composite gluon coupling

- Couplings between composite site gluon and down type quarks are diagonal but not universal in the quark basis before EWSB, thus leading to non-diagonal couplings after unitary rotation into quark mass eigenstates:

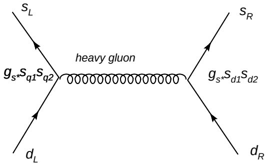


$$g_{*s} D_L^\dagger \begin{pmatrix} s_{q1}^2 & 0 & 0 \\ 0 & s_{q2}^2 & 0 \\ 0 & 0 & s_{q3}^2 \end{pmatrix} D_L$$

$$\Rightarrow g_{*s} s_{qi} s_{qj} G_\mu^* \bar{q}_L^i \gamma^\mu q_L^j \tag{3}$$

$\Delta F = 2$ process: ϵ_K

- Composite gluon mediates s, d mixing at tree level.



$$\Rightarrow C_{4K} \approx \frac{g_{*s}^2}{M_*^2} s_{q1} s_{q2} s_{d1} s_{d2} \approx \frac{g_{*s}^2}{M_*^2} \frac{2 m_d m_s}{v^2 Y_*^2} \qquad (4)$$

- Model independent bound (renormalized at 3 TeV): [UTfit Collaboration] [Csaki, Falkowski, Weiler, 2008]

$$\mathrm{Im}\, C_4 \lesssim \frac{1}{(\Lambda_F)^2}, \qquad \Lambda_F = 1.6 \times 10^5 \,\mathrm{TeV}. \qquad (5)$$

- Assuming order one phase

$$\Rightarrow M_* \gtrsim \frac{11 g_{*s}}{Y_*} \text{TeV} \tag{6}$$

- g_{*s} can be obtained from matching in corresponding warped extra dimension model that explains Planck-weak hierarchy.
  $g_{*s} \approx 6$ (tree level matching)
  $g_{*s} \approx 3$ (loop matching without brane term), smallest g_{*s} allowed.
- $Y_* <?$

Compare with warped extra dimension

$$Y_0 = a Y_{KK} f(c_L) f(c_R) \tag{7}$$

$$C_{4\ estimate}^{5D}(M_{KK}) = \frac{\left(g_5\sqrt{k}\right)^2}{Y_{KK}^2 a^2} \frac{2 m_s m_d}{v^2} \frac{1}{M_{KK}^2} \tag{8}$$

Bound on $M_{KK} \propto 1/a$.

β	a	$M_{KK},\ g_{s*} = 3$	$M_{KK},\ g_{s*} = 6$
0	1.5	3.7 TeV	7.4 TeV
1(two-site)	1	5.5 TeV	11 TeV
2	0.75	7.3 TeV	14.6 TeV
∞ (brane)	0.5	11 TeV	22 TeV [Csaki, et. al. 2008]

Table: We fix the composite/KK Yukawa coupling $Y_{KK} = 6$.

Rare decay $b \to s\gamma$

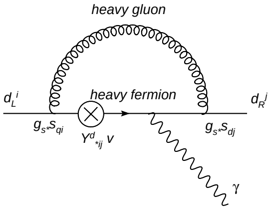
- Provides upper bound on Y_*.
- Effective Hamiltonian

$$\mathcal{H}_{eff}(b \to s\gamma) = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} [C_7(\mu_b) Q_7 + C_7'(\mu_b) Q_7' + \ldots]$$

$$Q_7 = \frac{e}{8\pi^2} m_b \bar{b} \sigma^{\mu\nu} F_{\mu\nu} (1 - \gamma_5) s; \quad Q_7' = \frac{e}{8\pi^2} m_b \bar{b} \sigma^{\mu\nu} F_{\mu\nu} (1 + \gamma_5) s \tag{9}$$

- C_7' is negligible in SM.

- Heavy gluon contribution:

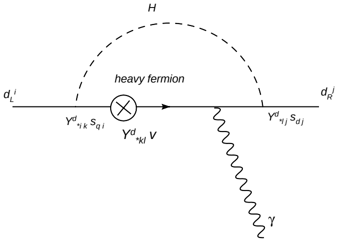


- Generates operator $C^G_{7\,ij}\bar{d}_j\sigma^{\mu\nu}F_{\mu\nu}(1-\gamma_5)d_i$ (before EWSB), with

$$C^G_{7\,ij} \propto s_{q_i} g^2_{s*} Y^d_{*ij} s_{d_j} \propto m^d_{ij} \tag{10}$$

- After unitary rotation into quark mass eigenstates, no flavor violating dipole operator is generated, thus no contribution to $BR(b \longrightarrow s\gamma)$

- Higgs and heavy fermion contribution:



$$C^H_{7\,ij} \propto s_{q_i} Y^d_{*ik} Y^d_{*kl} Y^d_{*lj} s_{d_j} \tag{11}$$

it is not aligned with m^d_{ij}, leading to flavor violating dipole operators.

$$C_7^{b\to s\gamma}(M_*) \approx -\frac{5}{48}\frac{(Y_*)^2}{(M_*)^2}\frac{\sqrt{2}}{G_F}; \quad C_7'^{b\to s\gamma}(M_*) \approx -\frac{5}{48}\frac{(Y_*)^2}{(M_*)^2}\frac{\sqrt{2}}{G_F}\frac{m_s}{m_b\lambda^4} \tag{12}$$

- $C_7^{\prime\text{new}}/C_7^{\text{new}} \approx 8$, different from SM.
- RG running from high to low scale suppress new contributions.
- Experiment: $\text{BR}(b \to s\gamma) = (352 \pm 23 \pm 9) \times 10^{-6}$ [HFAG]
  Theory: $\text{BR}(b \to s\gamma) = (315 \pm 23) \times 10^{-6}$ [Huber 2007]
- Allow 20% deviation from SM value

$$M_* \gtrsim (0.63) Y_* \text{ TeV} \tag{13}$$

- Combined with bound from ϵ_K

$$\begin{aligned} M_* &\gtrsim 2.6\sqrt{g_{s*}} \text{ TeV} \quad \text{for} \quad Y_* \approx 4.2\sqrt{g_{s*}} \\ &\approx 4.5 \text{ TeV for } g_{s*} \approx 3 \\ &\approx 6.4 \text{ TeV for } g_{s*} \approx 6 \end{aligned} \tag{14}$$

Other Flavor Observables

- Constraints from B meson mixing are weaker.
- Shift in $Z\bar{b}b$ coupling:

$$\frac{\delta g_{Z\bar{b}b}}{g_{Z\bar{b}b}} \approx \sum_{i=1}^{3} \left(\frac{Y_{*di3}}{Y_{*u33}}\right)^2 \left(\frac{m_t}{M_* s_{u3}}\right)^2 + \frac{1}{2}\left(\frac{m_t}{M_* s_{u3}}\right)^2 \left(\frac{g_{*2}}{Y_{*U33}}\right)^2 \quad (15)$$

gives similar bounds if no hierarchy between Y_*^u and Y_*^d.

- Predict large time dependent CP asymmetry in $b \to s\gamma$ (S_{CP}) due to large new physics contribution to C_7'.

Conclusion

- There exists a correspondence between bulk Higgs scenario and two-site model.
- Two-site model gives a very simple approach to analyze flavor physics.
- Exist tension between ϵ_K and $b \to s\gamma$ (opposite dependence on Y_*).
- $\sim O(5)$TeV composite scale could be consistent with flavor tests.
- Expect large time dependent CP asymmetry in $b \to s\gamma$.